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Low-frequency noise properties in Pt-indium gallium zinc oxide Schottky diodes

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The low-frequency noise properties of Pt-indium gallium zinc oxide (IGZO) Schottky diodes at different forward biases are investigated. The IGZO layer and Pt contact were deposited by RF sputtering at room temperature. The diode showed an ideality factor of 1.2 and a barrier height of 0.94 eV. The current noise spectral density exhibited 1/*f* behavior at low frequencies. The analysis of the current dependency of the noise spectral density revealed that for the as-deposited diode, the noise followed Luo's mobility and diffusivity fluctuation model in the thermionic-emission-limited region and Hooge's empirical theory in the series-resistance-limited region. A low Hooge's constant of 1.4×10^{-9} was found in the space-charge region. In the series-resistance-limited region, the Hooge's constant was 2.2×10^{-5}. After annealing, the diode showed degradation in the electrical performance. The interface-trap-induced noise dominated the noise spectrum. By using the random walk model, the interface-trap density was obtained to be $3.6 \times 10^{15}\,\mathrm{eV^{-1}\,cm^{-2}}$. This work provides a quantitative approach to analyze the properties of Pt-IGZO interfacial layers. These low noise properties are a prerequisite to the use of IGZO Schottky diodes in switch elements in memory devices, photosensors, and mixer diodes.
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Indium Gallium Zinc Oxide (IGZO) is a novel metal oxide semiconductor which is now an indispensable component in display industries.[1] The high mobility, low temperature fabrication process, amorphous structure and high uniformity make IGZO a useful alternative of conventional semiconductors.[2] In recent years, metal-IGZO Schottky diodes have drawn much attention due to their high frequency rectification properties and the application of IGZO in a variety of other devices such as metal-semiconductor field effect transistors[3] (MESFETs), radio-frequency energy harvestors,[4] and memory devices.[5] Owing to the recent achievements in the applications of IGZO Schottky diodes,[3–6] a detailed investigation of their properties and performance is required.

Low frequency noise (LFN) exists in all electronic devices, revealing the bulk and surface quality of semiconductors.[7] The main components of LFN are thermal noise, shot noise, flicker noise (also known as 1/*f* noise), and generation-recombination (G-R) noise.[8] Thermal and shot noises are white, simply related to the device resistance and current; therefore, at low frequencies studies on flicker and G-R noises are more important since such noises dominate the LFN at room temperature (RT) under bias.[8] LFN affects the sensitivity and resolution of integrated circuits, making it a major obstacle to many applications of Schottky diodes.[8,9] Analysis of LFN can also be used to improve the device performance and provide substantial information on physical properties. So far, the LFN properties of Schottky diodes have only been studied on crystalline semiconductors like gallium arsenide,[10–12] silicon (Si),[13–16] silicon carbide,[17] zinc oxide[18] and conventional amorphous semiconductors like a-Si.[19] The results often exhibit 1/*f* noise power spectral density which is proportional to I^n, where n varies from 1 to 2.[8] Several studies have investigated the LFN properties of IGZO thin film transistors (TFTs).[20–22] The noise performance is found to be comparable with the typical values of polycrystalline silicon TFTs.[23] However, since the remote phonon scattering caused by the dielectric layer contributes significantly to the noise performance of IGZO TFTs,[21] noise analysis of TFTs is not sufficient to describe the electrical properties of IGZO. Therefore, it becomes important to characterize the LFN of IGZO Schottky diodes experimentally.

In this letter, the LFN properties of as-deposited and thermally annealed Pt-IGZO Schottky diodes at RT with frequency varying between 1 Hz to 500 Hz are presented. The dependences of current noise and voltage noise spectral densities on bias are discussed. By adopting different noise models, the origins of LFN in IGZO Schottky diodes are evaluated.

Figure 1(a) shows the structure of a Pt-IGZO Schottky diode. SiO_2-Si wafers were used as the substrates and cleaned in an ultrasonic bath using water, acetone, and methanol sequentially. A 50-nm-thick Pt layer was deposited as the anode by radio-frequency (RF) sputtering at 80 W, 5×10^{-3} mBar in pure Ar. A gentle, 50-s-long oxygen plasma treatment at 50 W, 50 mTorr on the Pt surface was carried out to improve the quality of the Schottky barrier.[24] A 50-nm-thick IGZO layer with the molar ratio of 1:1:2 (In_2O_3:Ga_2O_3:ZnO) was also deposited by RF sputtering in

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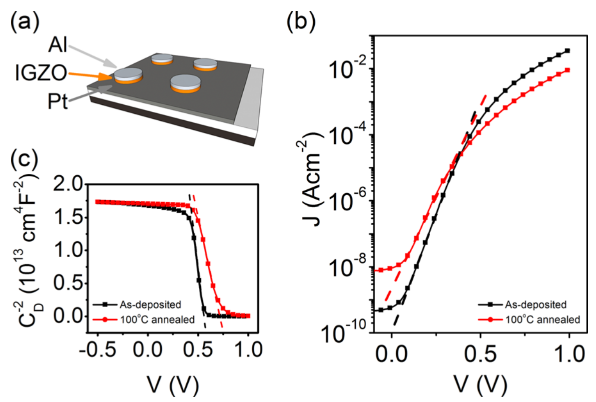

FIG. 1. (a) Schematic of the Pt-IGZO Schottky diodes. (b) J-V characteristics of the Schottky diode. (c) $1/C^2$ curve as a function of voltage. The slope gives the built-in voltage V_{bi} and the background doping density N_{bg}.

Ar and 3% O_2 mixed gas at 80 W. Then Al contacts were deposited by thermal evaporation and defined by a shadow mask. Finally, devices were placed in 20% acetic acid for 50 min in order to expose the anode and confine the active areas. Thermal annealing was performed at 100 °C in air for 1 h. The J-V and C-V properties were measured in the dark with an Agilent E5260B semiconductor analyzer and an Agilent E4980A LCR meter at RT, respectively. LFN was measured using a SR570 low noise current amplifier and a NI USB-6211 data acquisition module at different bias in an isolated metal box at RT.

In Fig. 1(b), it shows the J-V characteristics of a Pt-IGZO Schottky diode with a radius of 0.5 mm. The linear part in the log scale indicates the current is limited by the thermionic emission. The relation can be expressed by[25]

$$J = A^*T^2 \exp\left(-\frac{q\varphi_b}{kT}\right)\left\{\exp\left[\frac{q(V - JR_s)}{nkT}\right] - 1\right\}, \quad (1)$$

where A^* is the Richardson constant which equals 41 A cm^{-2} K^{-2}, T is the temperature, k is Boltzmann constant, n is the ideality factor which describes the uniformity of the Schottky barrier, φ_b is the barrier height, and R_s is the series resistance. For the as-deposited diode, the barrier height is found to be 0.94 eV and the ideality factor is 1.2. An ideality factor this close to unity suggests that thermionic emission is the primary mechanism of transport at low voltages. Figure 1(c) shows the room temperature C-V properties of the diode at 10 kHz. The background doping density, N_{bg}, and the built-in voltage, V_{bi}, can be determined from the C_D^{-2}-V curve by using[26]

$$C_D^{-2} = \frac{2\left[V_{bi} - V - \left(\frac{kT}{q}\right)\right]}{q\varepsilon_s N_{bg}}, \quad (2)$$

where ε_s is the permittivity of IGZO and equals 1.15×10^{-12} F cm^{-1}, a value obtained from the fully depleted capacitance of the diode at negative biases. From the linear fitting which corresponds to the bulk of IGZO, V_{bi} is found to be 0.55 V and N_{bg} is 8.63×10^{16} cm^{-3} for the as-deposited diode. The series resistance obtained from the J-V curve is found to be 5.4 Ω cm^2. The Hall measurement revealed that the IGZO film had a carrier concentration of 1.70×10^{12} cm^{-3} and a mobility of 3.6 cm^2 V^{-1} s^{-1} at RT. The energy gap between the conduction band minimum and Fermi level, (E_c - E_f), is found to be 0.40 eV by using $E_c - E_f = kT \ln(N_c/n_e)$ where N_c is the effective density of states. As for IGZO, the effective electron mass in the conduction band, m^*, equals to $0.34m_0$, making $N_c = 5.0 \times 10^{18}$ cm^{-3}.[27,28] Since $\varphi_b = qV_{bi} + (E_c - E_f)$, the barrier height from C-V measurements of the as-deposited diode is 0.95 eV, which is slightly higher than the barrier height from the J-V measurements. The difference is caused by image force lowering and the inhomogeneities in the barrier height.[29,30] After annealing the diode at 100 °C in air for 1 h, the J-V and C-V characteristics exhibit appreciable degradation in performance. The ideality factor increases to 2.1. The barrier height obtained from the J-V characteristics drops to 0.85 eV. From the C-V curves, N_{bg} increases to 1.51×10^{17} cm^{-3} and V_{bi} is found to be 0.71 V. The decrease in barrier height and the increase in N_{bg} are attributed to interface states.[30]

The LFN properties at different forward biases are shown in Figs. 2(a) and 2(b). The bias voltage varies from 0.25 V to 1.20 V. It is clear that the current noise, S_I, is proportional to $1/f$ at low frequencies, which means that the LFN of IGZO Schottky diode is dominated by flicker noise. At high frequencies, the current spectral density becomes flat due to the background noise generated from current amplifiers. No G-R noise is found in the current spectral density.

In order to further analyze the noise properties, a plot of the current spectral density at 10 Hz as a function of the device currents is shown in Fig. 3(a). For the as-deposited diode, two separate regions can be discerned in the current dependencies of S_I. The gradient is found to be proportional to I at low currents and I^2 at high currents. For the thermally annealed diode, the current spectral density is found to be slightly higher and proportional to I^2. In Fig. 3(b), it shows the current dependencies of the voltage noise, S_V, by using the relation $S_I/I^2 = S_V/V^2$. The thermally annealed diode still shows a higher voltage noise than the as-deposited device.

In the last few decades, the LFN properties of Schottky diodes have been widely discussed.[13,14,31–34] However, to date, most of the models remain debatable and are difficult

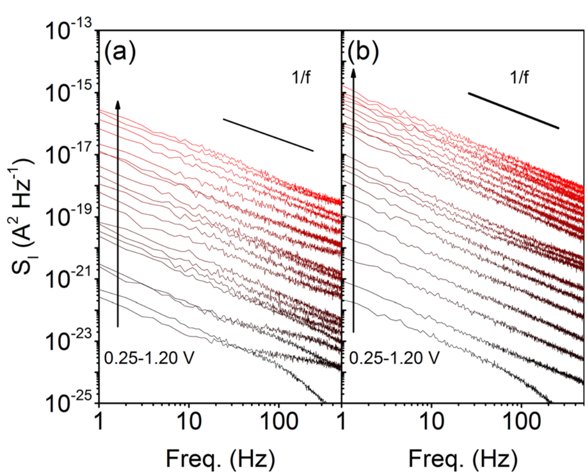

FIG. 2. Current spectral density S_I as a function of frequency of (a) the as-deposited and (b) the thermally annealed Pt-IGZO Schottky diode. The applied bias varies from 0.25 V to 1.2 V.

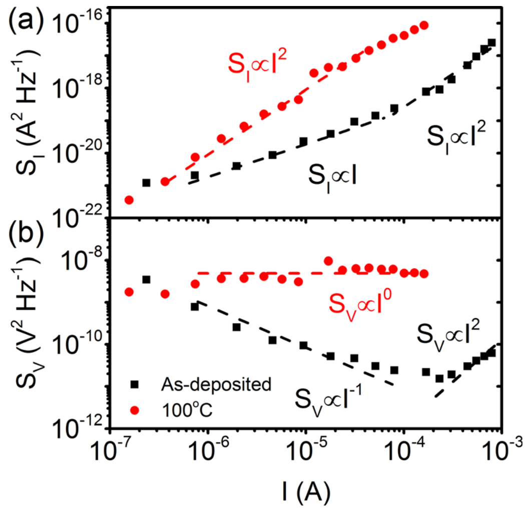

FIG. 3. (a) Current noise S_I and (b) voltage noise S_V as a function of forward current at 10 Hz.

to validate experimentally. In general, the dominant LFN comes from two separate sources, namely, series resistance and space-charge. Three theories can be used to explain the noise properties generated in the space-charge region, which are mobility and diffusivity fluctuation model,[35] trapping and tunneling model,[31] and random walk model.[32,33] The mobility and diffusivity fluctuation model was first proposed by Kleinpenning in 1979.[35] In the late 1980 s, Luo *et al*. corrected Kleinpenning's model and developed a widely accepted theory to describe the thermal emission limited noise,[13] which is given by

$$S_I = \alpha_H \frac{I}{f} \left(\frac{v_r}{v_d}\right)^2 \frac{q^3}{3} \left(\frac{N_D(V_{bi} - V)}{q\varepsilon_s \pi kTm^*}\right)^{0.5}, \tag{3}$$

where v_r is the electron recombination velocity, v_d is the drift velocity, $m^* = 0.34m_0$ is the effective electron mass in the IGZO,[29] and α_H is the Hooge's constant. It is found that the current spectral density is roughly proportional to I. For the trapping and tunnelling model and random walk model (RWM), S_I should be proportional to I^2. The trapping and tunnelling model assumes an energetically uniform bulk trap distribution. The RWM only relates to the interface-trap density, D_{it}, which can be expressed as

$$S_I = \frac{0.1}{f} \left(\frac{qI}{4\varepsilon_s}\right)^2 \frac{q^2 D_{it}}{kT\pi N_{bg} WAm^*}, \tag{4}$$

where W is the depletion width and A is the active area of the diode. It suggests that the random walk of electrons in interfaces via interface states contributes to the LFN.

In the series resistance limited region, the current noise becomes dominated by the IGZO bulk resistance. According to the Hooge's empirical equation,[36] the relation is found to be

$$S_{I,series} = \frac{I^2 \alpha_H}{f n_{e-total}} = \frac{I^2 \alpha_H}{f n_e A d}, \tag{5}$$

where $n_{e\text{-}total}$ is the total free carrier number in the IGZO layer and d is the thickness of the IGZO layer. It shows that S_I is also proportional to I^2.

Since the interface-trap-induced noise, the trapping and tunnelling noise, and the mobility-and-diffusivity-fluctuation-induced noise are generated in the depletion region, the voltage noise, S_V, is related to the dynamic resistance in the depletion region which is described as dV/dI. The series-resistance-induced voltage noise is related to the series resistance. Then the total voltage noise can be expressed as

$$S_V = S_{I,space-charge} \left(\frac{dV}{dI}\right)^2 + S_{I,series} R_s^2, \tag{6}$$

where $S_{I,space\text{-}charge}$ is the current noise generated in the space-charge region and $S_{I,series}$ is the current noise caused by the series resistance. When the current is limited by the barrier height, according to the thermionic emission theory, $(dV/dI)^2$ is proportional to I^{-2}. Thus, three different current dependencies of S_V can be found referring to the trap-induced noise, mobility-and-diffusivity-fluctuation-induced noise, and R_s-induced noise, respectively.

For the as-deposited diode, it is found that $S_V \propto I^{-1}$ and $S_I \propto I$ at low voltages, revealing that the LFN follows the mobility and diffusivity fluctuation model. At high biases, the LFN is dominated by the series resistance because $S_V \propto I^2$ and $S_I \propto I^2$. For the thermally annealed diode, the trap-induced noise dominates the noise spectrum at low frequencies. Since the degradation in the J-V properties suggests that the current is affected by the interface traps[30] and thermal annealing helps to reduce the bulk traps,[1] the random walk of electrons at the interface is considered as the origin of the LFN.[32] As the RWM has only been studied on conventional semiconductors, applying such model in the analysis on LFN properties of IGZO Schottky diodes has a significant contribution.

According to Eq. (3), the Hooge's constant, α_H, of the as-deposited diode is found to be 1.4×10^{-9} in the space-charge region as shown in Fig. 4, which is in the same order of magnitude as the values obtained from Si Schottky diodes ($\sim 10^{-9}$).[13–16] Due to the amorphous structure of IGZO, such a low α_H indicates the origin of scattering should be different from the crystalline semiconductors. In conventional semiconductors such as Si and GaAs, the ionized impurity scattering causes the decrease in the mobility when increasing the impurity concentration.[25] For IGZO, the mobility increases with the carrier concentration which is opposite to

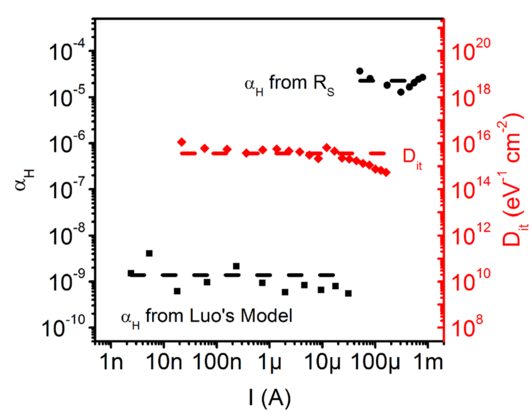

FIG. 4. Hooge's constant of the as-deposited diode and interface-trap density of the thermally annealed diode as a function of current.

the phenomenon observed in crystalline semiconductors.[37] The difference is caused by the unique electron transport properties of IGZO, described by the percolation model.[37–39] The carriers are scattered by the potential barriers above the mobility edge with the average height of 30–100 meV.[38] Since in the space-charge region, qV_{bi} is much larger than the distributed potential barriers, the electrons which are able to overcome the Schottky barrier have little interference from the disordered potential roughness. However, when the current reaches the series resistance dominated regime, according to the Hooge's empirical equation, α_H is found to be around 2.2×10^{-5} as shown in Fig. 4. This suggests that the scattering of electrons by the distributed potential barriers becomes more significant in the flat band region. Compared with the $\alpha_H = \sim 10^{-3}$ obtained from IGZO TFTs,[22] α_H in the series resistance regime is two orders of magnitude lower, which implies that the remote phonon scattering from the dielectric is not negligible. In IGZO, the carrier transport occurs between the metal *s* orbitals that compose the conduction band minimum.[37] Compared with the sp^3 orbitals in crystalline Si, the metal *s* orbitals make both electron transport and α_H less sensitive to bulk defects and disordered structure.[20]

After annealing, the diode shows degradation in the electrical performance and an increase in the LFN. By using Eq. (4), it is found that the interface-trap density is $3.6 \times 10^{15}\,\mathrm{eV^{-1}\,cm^{-2}}$ as shown in Fig. 4. Since the Schottky junction is sensitive to the oxygen content at the interface,[24] the O_2 plasma treatment on Pt and the excess O_2 during the deposition of IGZO are used to reduce Fermi level pinning by removing the hydroxide-induced layer and creating an oxygen-rich phase at the interface. However, according to previous studies,[40,41] the thermal annealing at temperatures below 150 °C may cause irreversible damage to Schottky interfaces. The LFN properties suggest that the thermal annealing process may cause defects in the oxygen-rich interfacial layer and create more interface traps, resulting in significant degradation in the diode performance. For other Schottky contacts with the existence of oxides, the interface-trap density is normally higher than $10^{14}\,\mathrm{eV^{-1}\,cm^{-2}}$,[42–45] which is similar to the obtained value. However, for the single-crystal Schottky diodes such as Au/n-GaAs and TiN/n-Si, the interface-trap density is found to be around $10^{12}\,\mathrm{eV^{-1}\,cm^{-2}}$,[12,13,15] which is as expected much smaller. As shown in Fig. 3(a), due to the oxygen-rich interface and the degraded electrical performance, the current noise of the thermally annealed diode became more than 100 times larger than that obtained from the as-deposited device. For the as-deposited diode, the LFN was dominated by the mobility-and-diffusivity-fluctuation-induced noise, making it impossible to determine the exact contribution of the interface-trap-induced noise. Nevertheless, because the interface-trap-induced noise was much smaller than the mobility-and-diffusivity-fluctuation-induced noise for the as-deposited diode, by using Eq. (4) and S_I at 0.65 V, D_{it} should be less than $5.71 \times 10^{12}\,\mathrm{eV^{-1}\,cm^{-2}}$, in terms of which the IGZO Schottky diodes become comparable with Si or GaAs devices. It is plausible that after the thermal annealing, the interface trap density increased from around $10^{12}\,\mathrm{eV^{-1}\,cm^{-2}}$ to $3.6 \times 10^{15}\,\mathrm{eV^{-1}\,cm^{-2}}$.

In this letter, the LFN of Pt-IGZO Schottky diodes was measured and analyzed. At room temperature, devices showed 1/*f* noise at low frequencies. Two different current dependencies of S_I were discovered. By plotting S_V as a function of current, the origins of the LFN for the as-deposited diodes were found to be different from the degraded diodes. According to the experimental data, for the as-deposited diode, the Hooge's constant was found to be 1.4×10^{-9} in the space-charge region and 2.2×10^{-5} in the series resistance limited region. Compared with the value obtained in IGZO TFTs, due to the absence of remote phonon scattering in the dielectric, α_H was found to be much lower. For the thermally annealed diode, the LFN follows the RWM. The interface-trap density was found to be $3.6 \times 10^{15}\,\mathrm{eV^{-1}\,cm^{-2}}$. Our work demonstrates the LFN measurement can determine a few material and interface physical parameters that cannot be obtained from DC measurements, including Hooge's constant and interface-trap density. The low noise characteristics also make IGZO Schottky diodes an attractive proposition for noise sensitive applications such as microwave detectors, frequency mixers, photosensors, and memory devices.

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